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Japan's Energy Scenarios Toward 2050

Topic 1 Strategies for Reducing Power System Costs

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Challenges of Large-Scale VRE Integration

- Growing energy security concerns are driving renewable energy deployment.
- While the power generation costs of VRE have declined, **reducing total power system costs**, including integration costs, remains a key challenge.

Characteristics of VRE and Associated Integration Costs

Output variability

Generation–demand mismatch
(**Profile costs**)



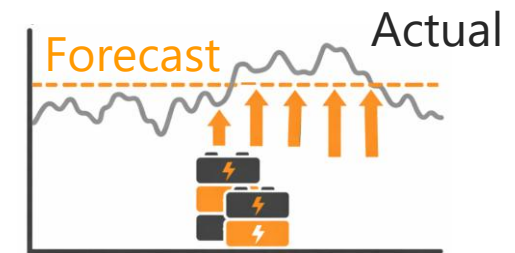
Geographic constraints

Grid expansion
(**Grid-related costs**)



Output forecast uncertainty

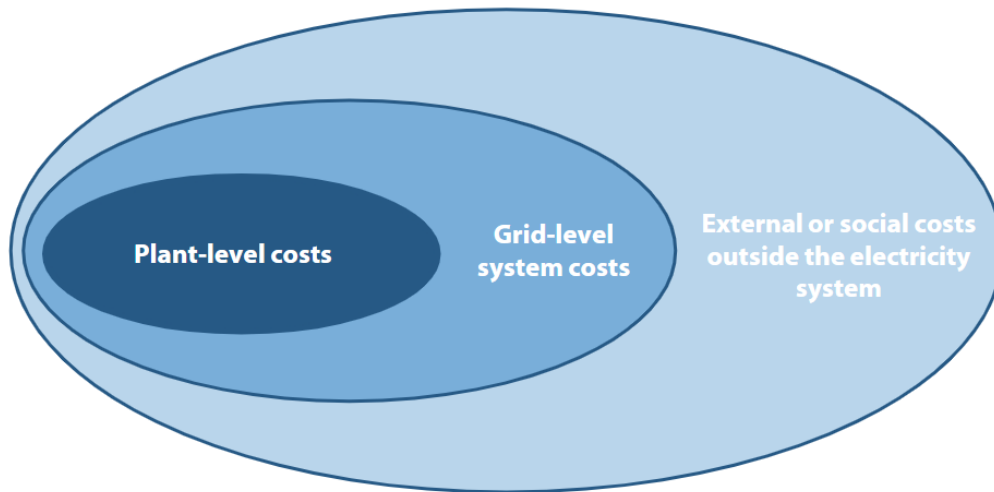
Balancing costs caused by
forecast errors
(**Balancing costs**)



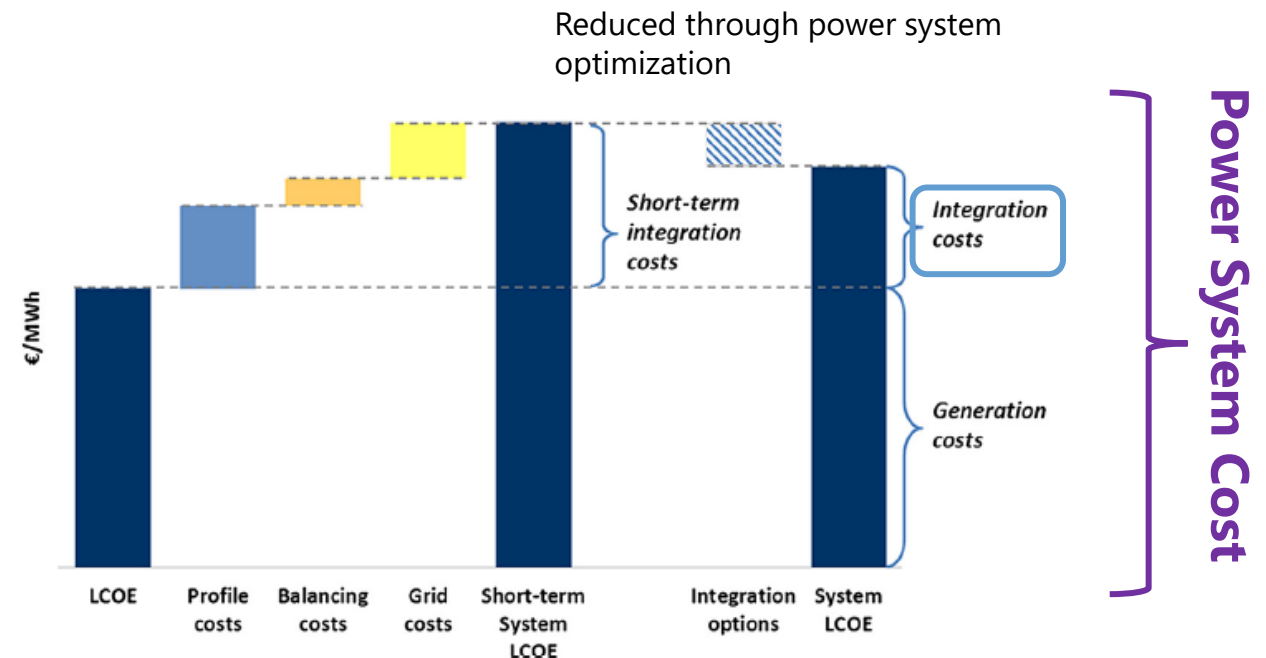
Definition of Power System Cost

- This study defines power system cost as: **LCOE + Integration Costs**
(Based on OECD/NEA [2]–[4])
- Reducing power system costs, rather than LCOE alone, is essential for energy policy.

Cost Components of VRE Integration



Source: NEA, 2012b.



Source: Adapted from Ueckerdt et al. [1].

Source: Adapted from OECD/NEA [3] [4].

Power System Cost Assessment in This Study

- Technology-specific power system cost estimates have been shown to be **highly scenario-dependent** [5][6].
- This study evaluates **whole-system costs** and compares relative cost differences across scenarios.

Integration Cost Components Considered in This Study (Black: Included Gray: Excluded)

Profile Costs

Thermal backup capacity cost
Curtailment cost

Battery investment cost
Battery losses
Hydrogen storage investment cost
(Thermal start-up and shut-down costs)
(Thermal part-load operation costs)
(Penalty cost for unserved electricity)

(Thermal part-load standby costs)
(Efficiency losses from thermal Load-following operation)

Balancing Costs

Grid-related Costs

Interregional transmission expansion costs (Distribution network expansion costs)
(Substation expansion costs)

- Some cost components overlap across categories. Only the major cost components are shown.

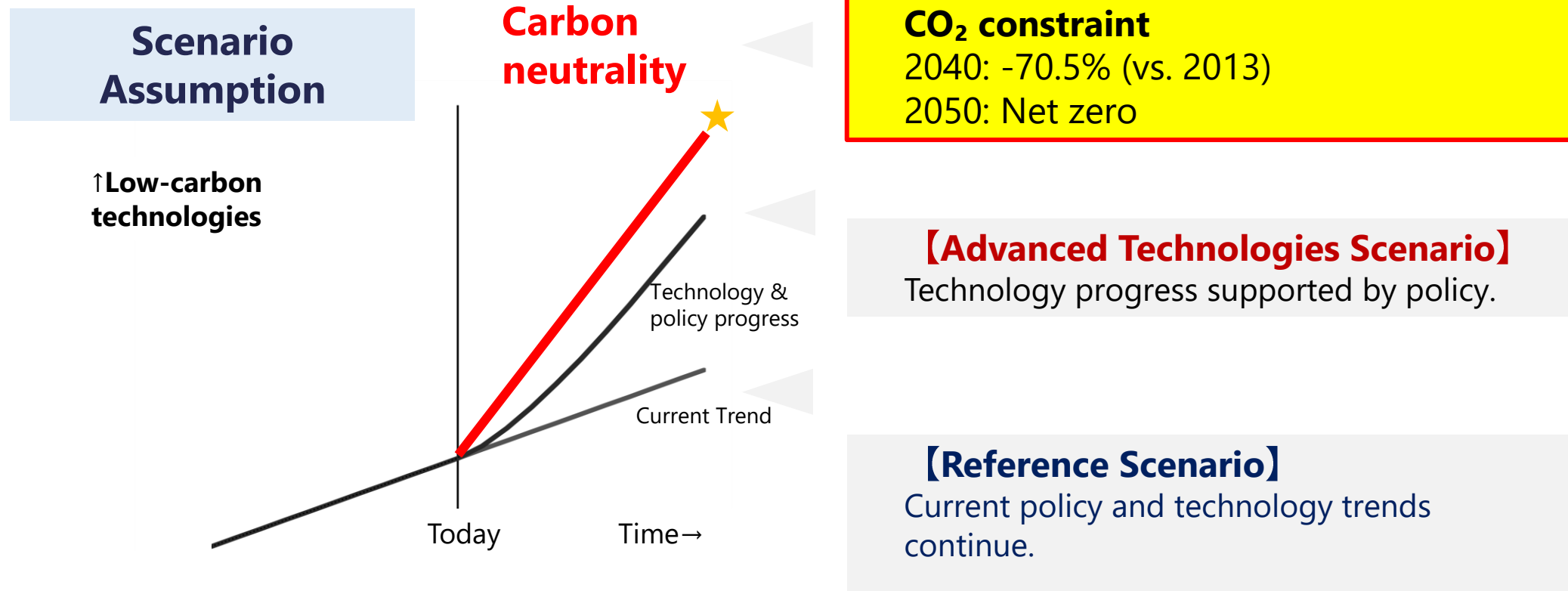
Scenario Settings

In addition to the Base Case for achieving carbon neutrality by 2050, four scenarios representing demand- and supply-side measures are analyzed.

	Description
Base Case	No additional measures.
EV Demand Response	26% of EVs participate in demand response (DR), based on the ENTSO-E Distributed Energy scenario [7].
Low-Cost Battery	Lower battery costs through technology improvements. Base: 33,800 JPY/kWh (NREL Mid Case [8]) Low-cost: 12,900 JPY/kWh (IEA NZE [9])
Expanded Nuclear	Maximum lifetime extension of existing plants and full operation of planned new reactors. Base: 27 GW Expanded: 41 GW
Combined Measures	All three measures are implemented.

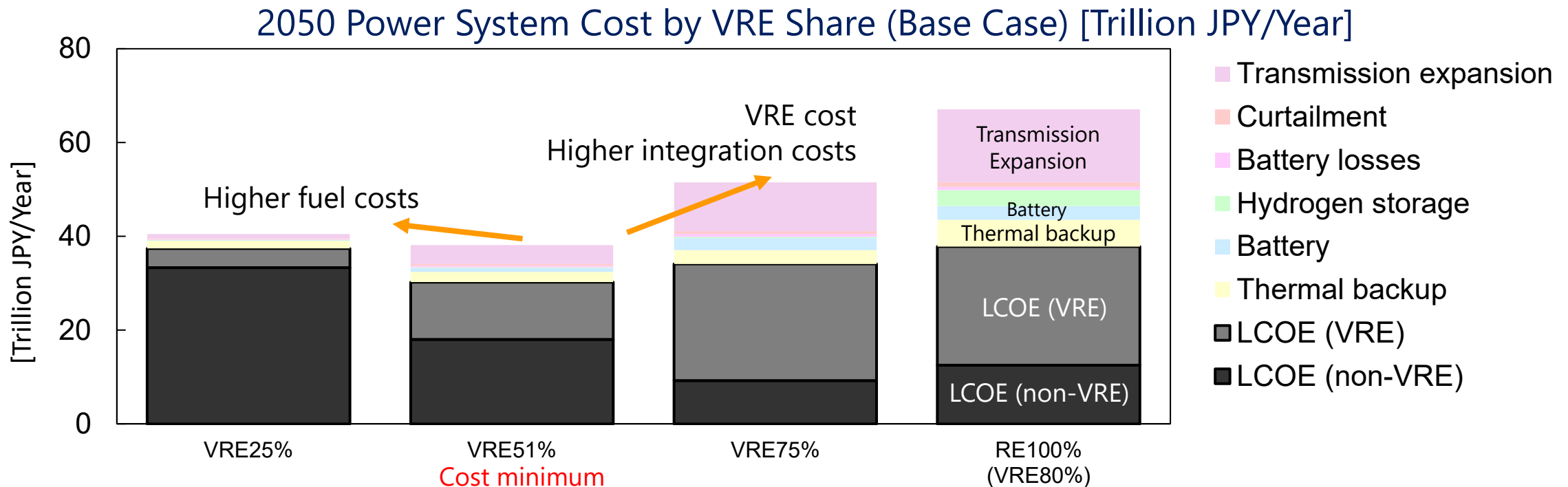
Carbon Neutrality Constraint

- This study assumes **carbon neutrality** by 2050.
- Therefore, its CO₂ emission assumptions differ from those of the IEEJ Outlook.



Power System Costs at Different VRE Shares (Base Case)

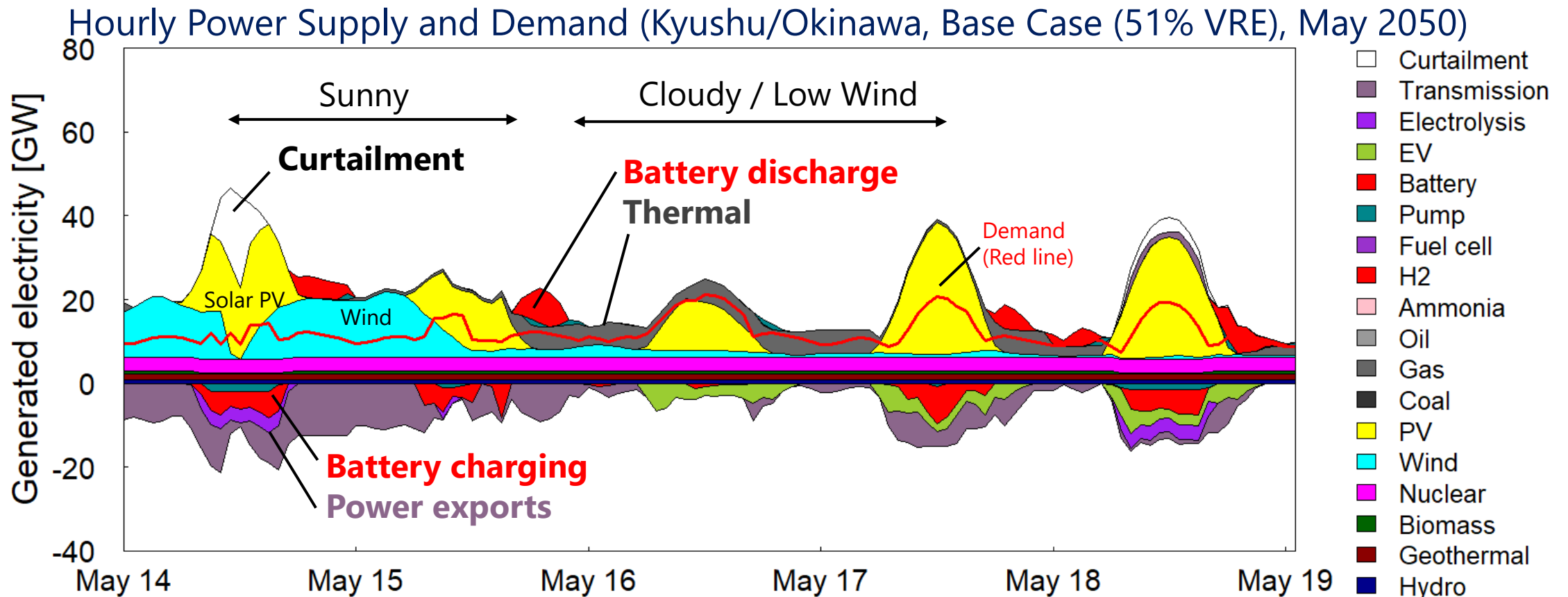
- In the Base Case, power system cost is minimized at a **51% VRE share**.
- Beyond this level, integration costs outweigh fuel savings, **increasing total system costs**.



- The optimal VRE share depends on system flexibility and fuel prices.
- At 100% renewable electricity, thermal backup is provided by biomass and green hydrogen.
- Hydrogen-fired generation costs are included in LCOE (Non-VRE).

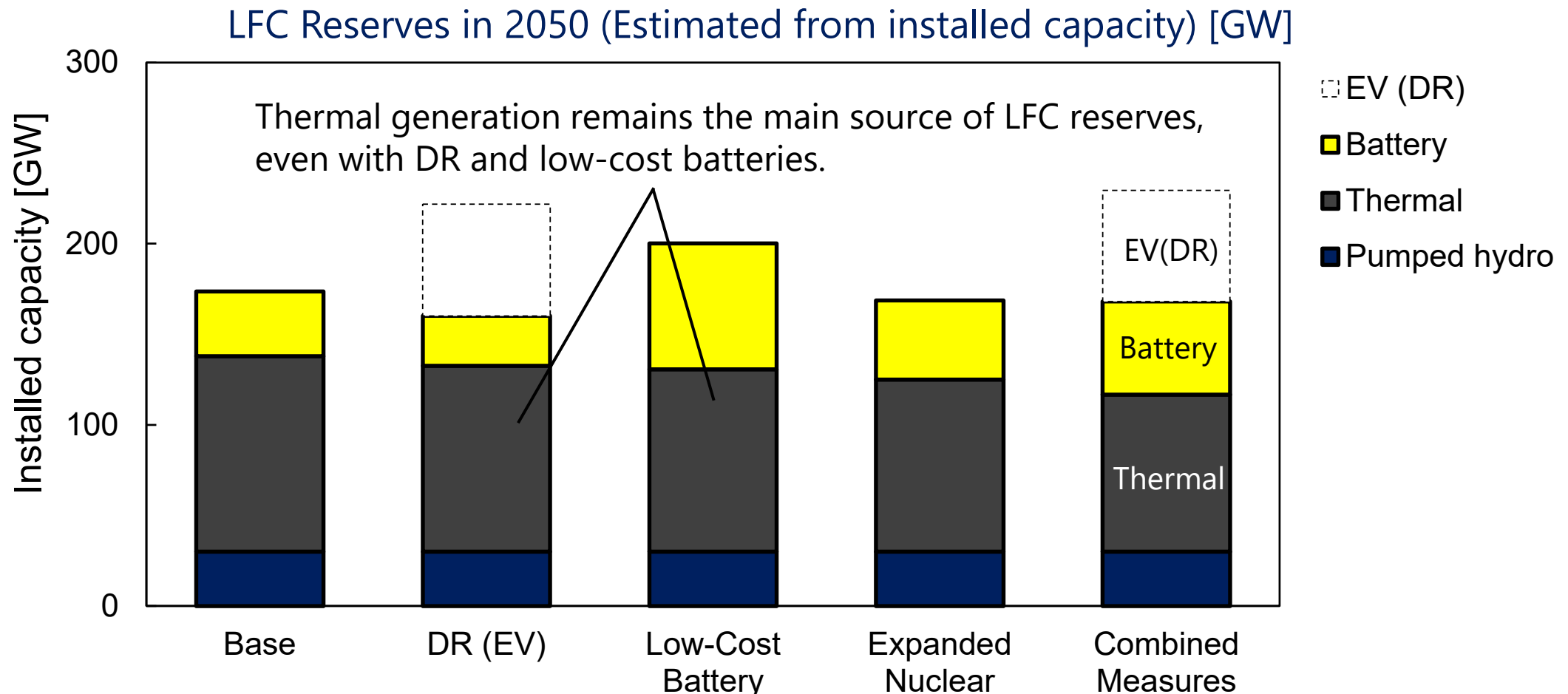
Power System Operation in 2050 (Base Case)

- At 51% VRE, 30–40% of VRE output is curtailed during solar peak hours on sunny days.
- During prolonged low-VRE output periods, backup from thermal power is essential, resulting in higher integration costs.



LFC Reserves in 2050

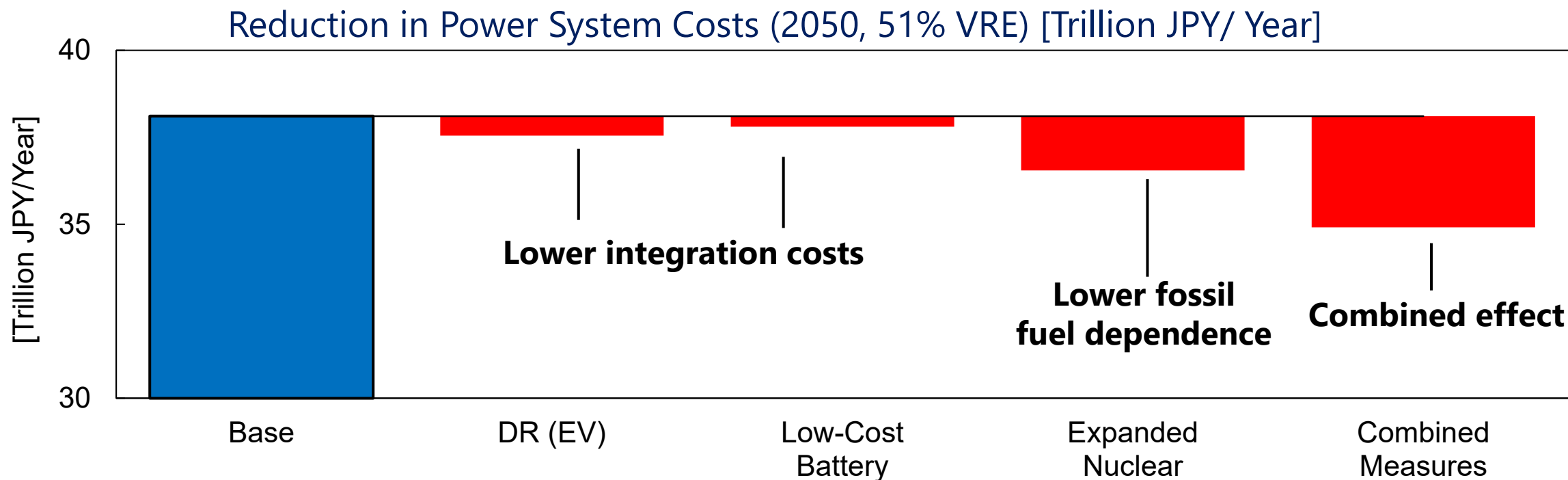
- Even with the demand response (DR) using EVs and low-cost batteries, **thermal power plants** remains the primary source of LFC reserve capacity.



- Thermal generation includes CCS gas, ammonia, hydrogen, and biomass.

Power System Cost Reduction in 2050 (51% VRE)

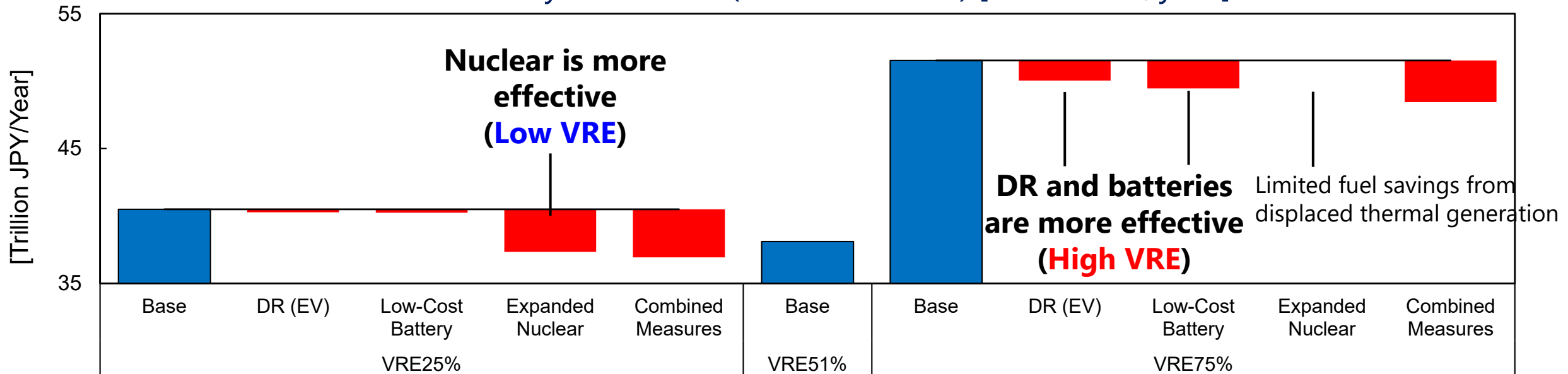
- At the optimal 51% VRE share, nuclear power reduce total system costs **by lowering fossil fuel use**.
- Demand response and low-cost batteries further **reduce integration costs**.



Cost Reduction at Different VRE Shares

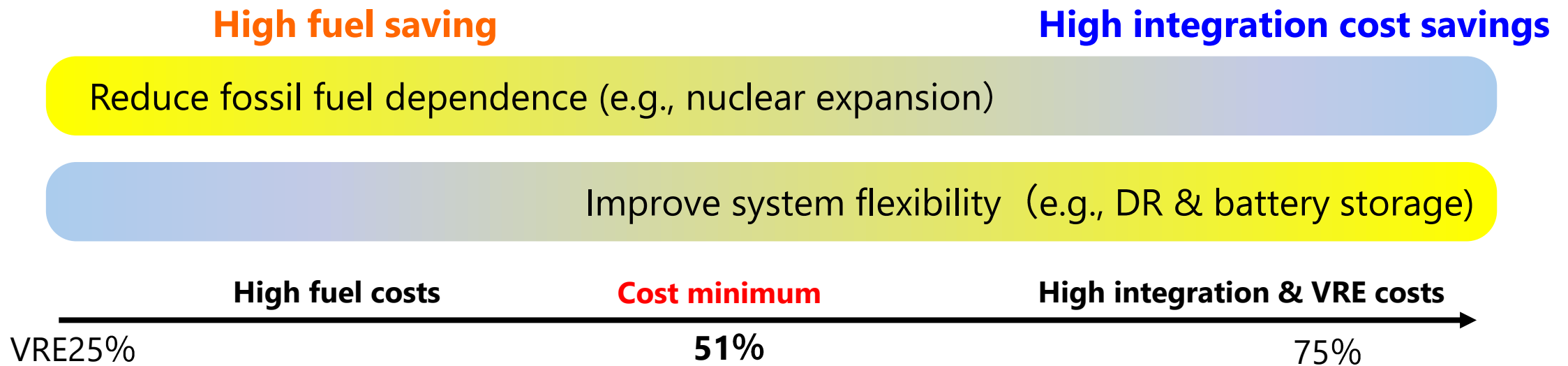
- At 25% VRE, **nuclear power** provides the largest cost reduction.
- At 75% VRE, **DR** and **low-cost batteries** become more effective.

Cost Reduction by VRE Share (VRE25% • 75%) [Trillion JPY/year]



Policy Implications

- In the Base Case, power system cost is minimized at a **51% VRE share**.
- The most effective measures for reducing power system costs **depend on the VRE penetration level**.
- A **phased transition strategy** is needed to balance energy security and cost reduction.



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Supplements

Components of Integration Costs

- Integration costs can be classified into **three categories** [1]*.
- Some cost components **overlap** across categories [2].

Profile Costs

Costs due to **generation–demand mismatch**

- Thermal backup capacity cost
- Curtailment cost
- Battery investment cost
- Battery losses
- Hydrogen storage investment cost
- Start-up / shutdown costs
- Part-load operation

Grid-related Costs

Costs due to **grid expansion**

- Interregional transmission expansion costs
- Distribution network expansion costs
- Substation expansion costs

Balancing Costs

Costs due to **forecast errors**

- Thermal part-load standby costs
- Efficiency losses from thermal Load-following operation

• Some studies treat capacity costs as a separate category [2]. In this study, they are included in profile costs.

Key Assumptions

Capital Cost	Based on the Procurement Price Calculation Committee [10]. For offshore wind: Base cost: 600,000 JPY/kW (2045) [11]. Adjusted for water depth and distance from shore [12].
Fuel Price	Based on 2022 CIF import prices and the IEA WEO 2024 NZE fuel price trend.
Interregional Transmission	Unit costs are based on the OCCTO Master Plan [13],[14]. No transmission capacity limit is assumed.
Maximum Renewable Energy Capacity	Residential rooftop PV : Roof orientation (S: 49.0 GW , E: 48.6 GW , W: 48.6 GW) [15]. Commercial rooftop PV : Building database (137.2 GW) [15]. Ground-mounted PV : Areas with limited local restrictions (52.3 GW) [15]. Agrivoltaics : All farms install up to 50 kW (41.9 GW) (based on [16]). Onshore wind : Areas with limited local restrictions (25.2 GW) [15]. Offshore wind : Water depth, capacity factor, and available area [12].

* Capacity limits may differ from Ref. [15] because existing renewable installations (e.g., in forests) are included.

Approaches to Reducing Power System Costs

- Power system costs can be reduced through demand-, supply-, and grid-side measures.
- However, their **effectiveness at different VRE penetration** levels remains unclear.

	Measure	Examples
Demand-side	DR (commercial EVs, industrial loads) Battery optimization Long-duration energy storage	Netherlands: Flex-e [17] California: SGIP [18] Massachusetts: Connected Solutions [19] UK: LDES [20]
Supply-side	Reduce fossil fuel dependence to improve energy security	France: Nuclear lifetime extension & new builds [21] UK: More renewables & nuclear to reduce gas dependence [22]
Grid-side	Transmission expansion	EU: Cross-border transmission expansion [23]

Nuclear Power Scenario Assumptions

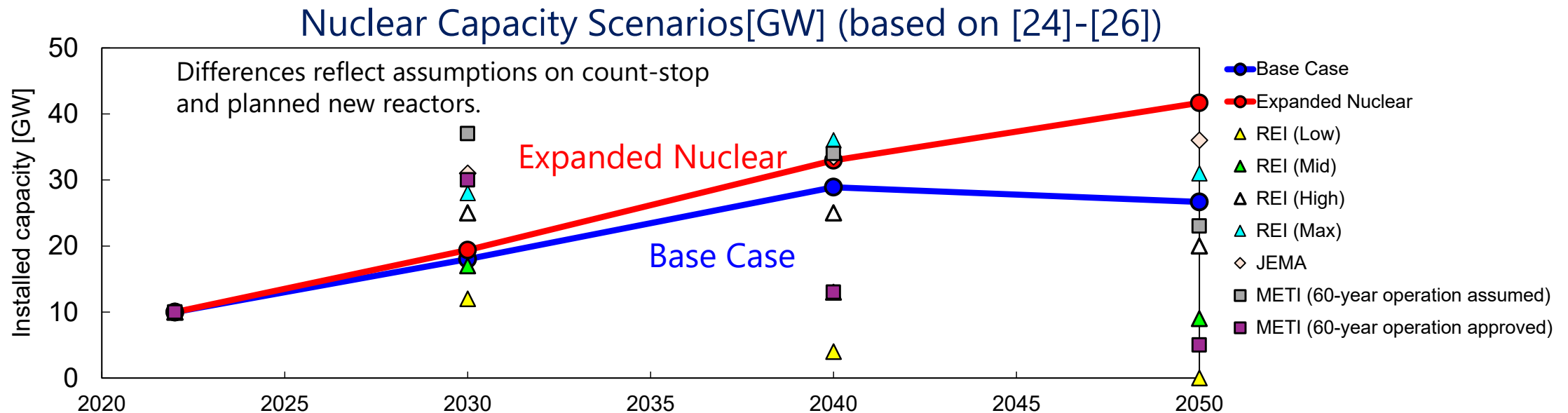
60-year lifetime assumed. Restart year by licensing status (March 2026):
Licensed: 2030, Under review: 2035, Not applied: 2040

Base Case

1970s reactors: retire by 2040. 1980s reactors: remain through 2050.
New builds: under construction only.

Expanded Nuclear

Existing reactors are fully utilized, including count-stop, and all restarted reactors remain in operation through 2050. Planned reactors are also included.



Reference: Count-Stop Policy

- Under the GX Decarbonized Power Source Act (2023, effective 2025), shutdown periods due to regulatory reviews or court orders can be excluded from the licensed operating period.
- However, reactors must pass aging management reviews every 10 years after 30 years of operation to continue operating.
- As reactor-specific count-stop periods are unavailable, this study applies a **uniform assumption**.